DESIGN OF A BIOLOGICALLY INSPIRED DIRECTIONAL ACOUSTIC SENSOR

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ABSTRACT

The development of a novel, biologically inspired acoustic sensor will be presented. The primary goal of this effort is to construct a miniature device that is capable of detecting the orientation of an incident sound source with an accuracy of 2°. The design approach follows from our investigation of the mechanics of directional hearing in the parasitoid fly, *Ormia ochracea*. This animal has been shown to be able to detect changes in the line of bearing as small as 2° [A. Mason, M. Oshinsky, and R. Hoy, "Hyperacute directional hearing in a micro-scale auditory system," *Nature* 4/5/01]. The tympanal structures of the ears of this animal suggest a novel approach to designing very small directionally sensitive microphones. Candidate microphone diaphragm designs are presented that are being fabricated using silicon microfabrication technology. Model results indicate that the design can achieve significant performance improvements over the conventional approach of making directional microphones. This includes a nearly 20 dB reduction in self-noise, and roughly a factor of 10 improvement in low frequency sensitivity.

1.0 INTRODUCTION

Any acoustic sensor that responds preferentially to sound from a specific direction must detect the spatial gradient in the sound that is incident on it. In current microphone technology, this is typically achieved either by constructing a pressure sensitive diaphragm driven on either side by sound sampled at different locations in the sound field, or by using two isolated microphones and processing the signals electronically. The distance between the locations at which the sound is sampled is normally smaller than the sound wavelength. It is well known that as the overall dimensions of the sensor are reduced, with a corresponding reduction in the spatial separation in the sensed pressures, the detected pressure difference will also be reduced. This loss of sensitivity poses numerous engineering challenges in the design of very small directional microphones. In the present study, we seek an improved design approach inspired by the auditory systems of small animals that are adept at localizing sounds.

Our approach to designing miniature directional microphones follows from our previous study of the auditory system of the parasitoid fly *Ormia ochracea* [1]. This animal has shown exemplary ability to localize sounds even though its ears span only about 1mm. The fly can detect changes in the angle of incidence of the sound that are as small as 2°[2]. In this fly, the detection of the pressure gradient is achieved by mechanically coupling the motions of the two ears. As a result, a difference in pressure at the exterior of the two ears causes them to move out-of-phase. The combination of this motion with an in-phase motion excited by the average pressure leads to a directionally sensitive response [1]. If one wishes to detect the pressure gradient using a very small device, this system suggests that an effective way to accomplish this is to design a sensor that rocks about a fulcrum due to differences in pressure at two points on its exterior. This differs from the usual approach of sampling the sound pressure at two points and arranging the device so that these pressures drive either the exterior or interior side of a single microphone diaphragm.

The aim of this paper is to describe a design study of this biologically inspired directional microphone concept. A model for the response of a conventional differential microphone is first described in which sound drives both the internal and external surfaces of the microphone diaphragm. Results from this model are then compared to those of a simplified model of the response of a microphone diaphragm based on Ormia's ears. The use of this approach

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Abstract

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opens up numerous design possibilities that have not previously been available. Because our current interest is in developing very small differential microphones, efforts are underway to construct the devices using silicon microfabrication techniques. Detailed designs have been developed with consideration given to a wide range of design parameters. It is concluded that the present approach is very well suited to fabrication out of silicon and it is anticipated that the performance will be significantly superior to that achievable with conventional approaches.

2.0 BIOLOGICAL INSPIRATION

In a previous study, we discovered that the mechanical structure of the ears of the parasitoid fly *Ormia ochracea* endows the fly with a remarkable ability to sense the direction of an incident sound wave [1]. The fly's auditory system has evolved in such a way that it is ideally suited to hearing and localizing a cricket's mating call. Measurements of the mechanical response of the ears of this fly indicate that when sound arrives from one side, the ear that is closer to the sound source responds with significantly greater amplitude than the ear which is further from the source. The interaural difference in mechanical response is due to the coupling of the ears' motion by a cuticular structure that joins the two tympana, which we have named the intertympanal bridge. This is the first report of the use of a mechanical link between a pair of ears to achieve directionally sensitive hearing [1].

An examination of the analytical model for the acoustic response of the tympana of *Ormia ochracea* shows that the system can be represented in terms of two, uncoupled resonant modes of vibration that are excited by a sound wave as shown in figure 1 below. A primary goal of the present investigation is to apply our understanding of the mechanics of this and similar auditory systems and mimic the operating principles used in order to construct an acoustic microsensor that is insensitive to unwanted noise disturbances. The ears of *Ormia ochracea* serve to demonstrate that such a small directional microphone, or "ormiaphone," can be developed.

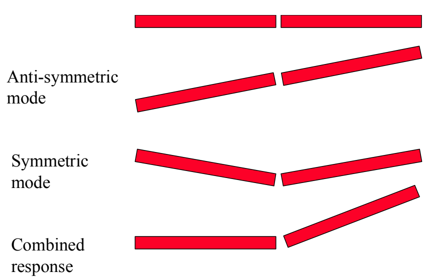


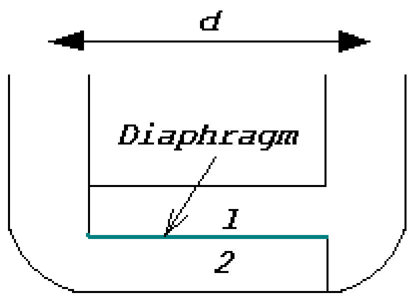
Figure 1. Modes of vibration of the intertympanal bridge. The anti-symmetric mode involves rocking of the bridge about the fulcrum and responds to the pressure gradient. The symmetric mode is a translational bending motion in which the two sides move in-phase and responds to the average pressure on the two sides. When the mechanical properties of the system are appropriate, the general response consists of a combination of the two modes where their contributions cancel on one side and add on the other.

3.0 DIFFERENTIAL MICROPHONE CONSTRUCTIONS

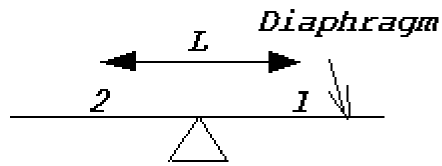
Differential microphones respond to the difference in pressure at two points in space. If d is the distance between these two points and ϕ is the angle of incidence of the sound relative to a line connecting the two points, then the net pressure, or pressure difference is given by

$$P_{net} \approx Pi\omega \frac{d}{c} \cos(\phi) \qquad (1)$$

where $i = \sqrt{-1}$, ω is the frequency in radians/s, P is the amplitude of the pressure, and c is the sound speed. The directivity pattern of this microphone is determined by $\cos(\phi)$ which gives it the shape of a "figure 8" as expected for a differential microphone.



(a) Conventional Differential Microphone



(b) Ormia-Inspired Microphone

Figure 2 Constructions of the differential microphone

A simplified representation of a conventional differential microphone is depicted in figure 2(a) in which a diaphragm is driven on both the top and bottom sides by sound that travels through two ducts having openings that are separated by a distance *d*. Our alternative approach, inspired by the ears of the fly, is depicted schematically in figure 2(b). In this case, sound drives only the top surface of the diaphragm. The difference in pressure at points *1* and *2* on the top surface produce a rocking motion about the pivot point. The right and left sides of the diaphragm thus move in opposite phase in response to a spatial pressure gradient. This construction introduces entirely new design possibilities for sensing pressure gradients.

In the following, a brief overview is presented of the operating principles used in the differential microphone designs shown in figure 2. The performance of specific designs is compared to illustrate some of the advantages of the present approach. Since our current interest is in the development of very small acoustic sensors, it is assumed that each design will be fabricated using silicon microfabrication techniques. The conventional microphone diaphragm used the approach shown in figure 2(a) is assumed to consist of a $1mm \times 2\ mm$ polysilicon plate that is clamped on all edges and has a thickness of 1 μm. The diaphragm shown in figure 2(b) is designed using a detailed finite element model so that it responds as a rigid plate that is supported on torsional springs at the pivot.

3.1 CONVENTIONAL DIFFERENTIAL MICROPHONE

Assume that the diaphragm is fabricated using a "conventional" approach so that it consists of a 1 μm silicon membrane having dimension $1mm \times 2\ mm$. The displacement of the diaphragm x_0 may be approximately modeled by

$$\ddot{x}_0 + \omega_0^2 x_0 + 2\omega_0 \zeta_0 \dot{x}_0 = f_0 / m_0 \qquad (2)$$

Where, ω_0 is the natural frequency, ζ_0 is the damping ratio, and m_0 is the total mass. f_0 the effective force due to the sound pressure

$$f_0 = P_{net} \alpha s_0 e^{i\omega t} \qquad (3)$$

s_0 is the area.

If it is assumed that the edges of the diaphragm are clamped, the mode shape can be taken to be the products of the eigenfunctions for a clamped-clamped beam. This gives

$$\alpha = \frac{\int_0^{l_x}\int_0^{l_y} \phi(x/l_x)\phi(y/l_y)\,dxdy}{\int_0^{l_x}\int_0^{l_y} \phi(x/l_x)^2 \phi(y/l_y)^2\,dxdy} \qquad (4)$$

Where,

$$\phi(z) = \cos(pz) - \cosh(pz) + D(\sin(pz) - \sinh(pz))$$

Where $p = 4.730040745$ and $D = -0.982502215$. Carrying out the integration in Eq. 4 gives

$$\int_0^{l_x}\int_0^{l_y}\phi(x/l_x)\phi(y/l_y)dxdy = 0.6903 s_0$$

and

$$\int_0^{l_x}\int_0^{l_y}\phi(x/l_x)^2\phi(y/l_y)^2 dxdy = s_0$$

So that $\alpha = 0.6903$.

As in Eq. 2, if we let $x_0 = X_0 e^{i\omega t}$,

Then from Eq. 3 and 1, the complex amplitude of the response becomes

$$X_0 = \frac{P_{net}\alpha s_0/m}{\omega_0^2-\omega^2+i\omega 2\omega_0\zeta_0} = \frac{P\alpha s_0 i\omega\frac{d}{c}\cos(\phi)/m}{\omega_0^2-\omega^2+i\omega 2\omega_0\zeta_0} \tag{5}$$

It is assumed that the response is detected using capacitive sensing with a back electrode that is distributed over the entire diaphragm area. The electrical output will then be proportional to the surface average of the deflection. The overall sensitivity of the conventional microphone S_0 may be obtained by multiplying the mechanical sensitivity by the electrical sensitivity V_b/h where V_b is the bias voltage and h is the thickness of the gap between the diaphragm and the back electrode.

$$S_0 = \frac{V_b}{hs_0}\frac{X_0}{P}\int_0^{l_x}\int_0^{l_y}\phi(x/l_x)\phi(y/l_y)dxdy = \frac{X_0}{P}\frac{V_b}{h}\alpha$$

$$= \frac{V_b}{h}\frac{s_0\alpha^2 i\omega\frac{d}{c}\cos(\phi)/m}{\omega_0^2-\omega^2+i\omega 2\omega_0\zeta_0} \tag{6}$$

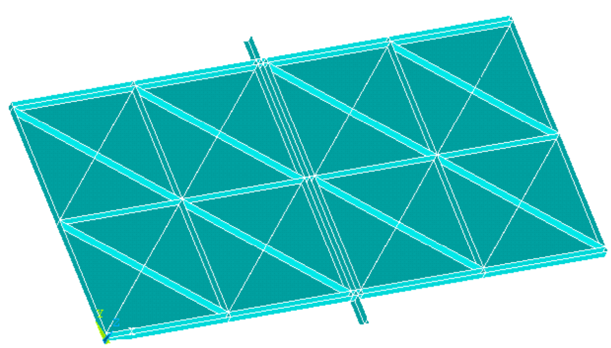


Figure 3. Ormia Differential Microphone design

3.2 ORMIA DIFFERENTIAL MICROPHONE

A structure that is designed to behave like the differential microphone of figure 2(b) is shown in figure 3. The structure consists of a *1mm* $\times$ *2 mm* polysilicon plate with stiffeners and is assumed to be attached to a rigid substrate only at the ends of a stiffener that protrudes from its midline. The diaphragm is designed so that its motion is dominated by rotation about this stiffener. The response of the diaphragm may be analyzed approximately as a rigid

body using a lumped parameter model, in which the parameters of the structure are obtained through a detailed finite element analysis. The diaphragm can be simplified as a rigid bar that possesses two degrees of freedom. Its motion can be represented by rotation about the centerline θ, and the displacement of the midpoint x. The equations of motion of the diaphragm are:

$$I_{yy}\ddot{\theta} + k_{t\_mech}\theta + 2r(L/2)^2\dot{\theta} = (f_1 - f_2)L/2 \tag{7a}$$

$$m\ddot{x} + kx + 2r\dot{x} = f_1 + f_2 \tag{7 b}$$

Where I_{yy} is the mass moment of inertia about the Y-axis; k_{t_mech} is the mechanical torsional spring constant of the support; r is the mechanical dashpot constant for equivalent dashpots attached to each side of the diaphragm; L is the distance between the centers of the two sides; f_1 and f_2 are the effective forces on each side due to the sound pressure; m is the mass of the diaphragm; and k is the transverse spring constant of the supports. It should be noted that in the present analysis the effects of capacitive sensing on the dynamic response of the diaphragm have been neglected. It is well known that the force due to the biasing electric field acts like a negative spring and reduces the resonant frequency of the system. An examination of these effects will be presented in a future report.

The forces acting on the top surface of the diaphragm due to a sound wave incident at an angle ϕ relative to the plane of the diaphragm may be expressed as

$$f_1 = Ps/2e^{i\omega(t+L/2\cos(\phi)c)} = F_1e^{i\omega t} \tag{8}$$

$$f_2 = Ps/2e^{i\omega(t-L/2\cos(\phi)c)} = F_2e^{i\omega t} \tag{9}$$

where, $s/2$ is the effective area of each side of the diaphragm; c is the speed of sound, $c = 344\ m/s$; $i = \sqrt{-1}$; ω is the frequency in radians/s.

Using Eq. 8 and 9, the right hand sides of Eq. 7a and b become

$$(f_1 - f_2)L/2 = L/2Psi\sin(\omega L/2\cos(\phi)c)e^{i\omega t} \approx Psi\omega(L/2)^2\cos(\phi)/ce^{i\omega t} \tag{10}$$

$$f_1 + f_2 = Ps\cos(\omega L/2\cos(\phi)c)e^{i\omega t} \approx Pse^{i\omega t} \tag{11}$$

Where we have assumed that since L is very small relative to wavelength of sound, i.e. $\omega L/2\cos(\phi)c << 1$.

Eq. (7), (10) and (11) enable the solutions for Σ and x to be written as

$$\theta = \Theta e^{i\omega t},\ x = Xe^{i\omega t}$$

Where,

$$\Theta = \frac{Psi\omega(L/2)^2\cos(\phi)/c}{k_{t\_mech} - \omega^2 I_{yy} + i\omega 2r(L/2)^2} = \frac{Psi\omega(L/2)^2\cos(\phi)/(cI_{yy})}{\omega_1^2 - \omega^2 + i\omega 2\zeta_1\omega_1} \tag{12}$$

$$X = \frac{Ps}{k - \omega^2 m + i\omega 2r} = \frac{Ps/m}{\omega_2^2 - \omega^2 + i\omega 2\omega_2\zeta_2} \tag{13}$$

ω_1 and ω_2 are the resonant frequencies of the rotational and translational modes respectively, $\omega_1 = \sqrt{\frac{k_{t\_mech}}{I_{yy}}}$, $\omega_2 = \sqrt{\frac{k}{m}}$,

ω is the driving frequency

ζ_1 and ζ_2 are the damping ratios.

The dashpot constant may be related to the properties of the rotational mode by $r = \dfrac{\omega_1 \zeta_1 I_{yy}}{(L/2)^2}$.

Note that the total equivalent dashpot constant is $R = 2r$ since there are two dashpots with dashpot constant r.

The displacements of the middle of each side of the microphone are given by

$$x_1 = X_1 e^{i\omega t} = x + \frac{L}{2}\theta = (X + \frac{L}{2}\Theta)e^{i\omega t} \tag{14}$$

$$x_2 = X_2 e^{i\omega t} = x - \frac{L}{2}\theta = (X - \frac{L}{2}\Theta)e^{i\omega t} \tag{15}$$

From Eq.s 12 and 13

$$X_1 = \frac{Ps/m}{\omega_2^2 - \omega^2 + i\omega 2\omega_2 \zeta_2} + \frac{L}{2}\frac{Psi\omega(L/2)^2 \cos(\phi)/(cI_{yy})}{\omega_1^2 - \omega^2 + i\omega 2\zeta_1\omega_1} \tag{16}$$

The supports are designed so that ω_2 is much larger than the frequencies of interest, so we can neglect the first term in Eq. 16 to obtain

$$X_1 \approx \frac{Psi\omega(L/2)^3 \cos(\phi)/(cI_{yy})}{\omega_1^2 - \omega^2 + i\omega 2\zeta_1\omega_1} \tag{17}$$

Since our goal is to detect the pressure difference and minimize the effect of the average pressure, it is very advantageous to sense the difference $x_1 - x_2 = L\theta$. This also provides a factor of two increases in sensitivity and help to minimize the effects of electromagnetic noise sources. If the thickness of the gap between the diaphragm and the backplate is h, and the bias voltage is V_b, as in Eq. 6, the overall sensitivity of the Ormia microphone S is then obtained using Eq. 12

$$S = \frac{X_1 - X_2}{P}\frac{V_b}{h} = \frac{L\Theta}{P}\frac{V_b}{h} = \frac{V_b 2si\omega(L/2)^3 \cos(\phi)/(cI_{yy}h)}{\omega_1^2 - \omega^2 + i\omega 2\zeta_1\omega_1} \tag{18}$$

From Eq. 18 it appears that there is a very strong dependence on the distance L between the centers of the two sides. To examine the sensitivity to this parameter it is important to note while the mass moment of inertia I_{yy} depend on the details of the mass distribution in the diaphragm to be concentrated as a distance $L/2$ from the pivot point. This give $I_{yy} \approx (L/2)^2 m$ so that Eq. 18 becomes

$$S \approx \frac{V_b Lsi\omega \cos(\phi)/(cmh)}{\omega_1^2 - \omega^2 + i\omega 2\zeta_1\omega_1} \tag{19}$$

The total sensitivity is thus roughly proportional to the distance L, and the area s, and is inversely proportional to the total mass m.

4.0 NOISE ESTIMATION

It is assumed that the noise in the device is dominated by the “self-noise” or thermal noise at the sensor as described by Gabrielson [3]. It is customary to characterize the noise performance of microphones in terms of the A-weighted overall noise output. To compute this, we estimate the noise in each octave band and sum the results after applying the A weighting. The octave band level may be computed from:

$$SPL_{ob} = 10\log\frac{P_{rms}^2}{P_{ref}^2} = 10\log\frac{P_s^2\Delta f}{P_{ref}^2} \text{ dB} \tag{20}$$

Where,

P_{ref} is reference rms (root mean square) sound pressure, usually $P_{ref} = 20\times 10^{-6}$ Pa for airborne sound

P_{rms} is the total rms sound pressure in Pa, which is associated with the octave bands, $P_{rms} = P_s\sqrt{\Delta f}$

P_s is the average rms sound pressure (*1-Hz* band), assume the continuous spectrum is "flat", $P_s = constant$. Let's simply set $P_s = 1$ Pa

Δf is the bandwidth of the octave bands

The equivalent dBA sound pressure level due to thermal noise in the microphone may be computed from (with no compensation filter to flatten the response):

$$N \approx 135.2 + 10\log_{10} P_{sd} \tag{21}$$

Where,

The number "*135.2*" comes from

$$10\log_{10}\frac{\sum_{i=1}^{11} 10^{(SPL_{ob_i}+Aweight_i)/10}\cdot p_{ref}^2}{p_{ref}^2} = 10\log_{10}\left(\sum_{i=1}^{11} 10^{(SPL_{ob_i}+Aweight_i)/10}\right) = 135.2 \ dB$$

Aweight is A-weighting relative response in *dB*

P_{sd} is the white noise power spectrum due to noise, $P_{sd} = 4k_bTR/s^2$ [3]

k_b is Boltzmann's constant, $k_b = 1.38\times 10^{-23}$ J/K

T is the absolute temperature, $T = 293$ K

s is the area over which the dashpots act

r is the dashpot constant, $r = \dfrac{\omega_1\zeta_1 I_{yy}}{(L/2)^2}$.

R is the total equivalent dashpot constant, $R = 2r$, since there are two dashpots with dashpot constants r. A rough estimate of $I_{yy} \approx (L/2)^2 m$. So, $r \approx \omega_1\zeta_1 m$.

Then the noise becomes

$$N \approx 135.2 + 10\log_{10}(8k_bT\omega_1\zeta_1 m/s^2) \tag{22}$$

Eq. 22 shows that the noise is minimized by designing a structure with a low resonant frequency for rotation motion, ω_1. The damping ratio ζ_1 should be as small as possible without resulting in unacceptable transient response. It is reasonable to design the damping in the system so that it is slightly overdamped giving $\zeta_1 \approx 1$. As noted above, we should strive to construct a diaphragm with the smallest mass m possible.

Noise estimation for the conventional differential microphone is similar with that described above for the Ormia microphone. Note, the equivalent dashpot constant should be $R_0 = 2\omega_0\zeta_0 m_0$.

In an attempt to conduct a fair comparison of the performance of the two designs, we need to find a compensation filter that would cause the microphones to have the same frequency response. The "ideal" frequency response is set arbitrarily to have the level of the Ormia differential microphone at its most sensitive frequency and be flat from *200 Hz* to *10 kHz*. This should be set to zero outside the frequency range from *200 Hz* to *10 kHz*. This frequency range corresponds to the 5th through 10th octave band center frequencies.

The maximum sensitivity of the Ormia microphones occurs near $\omega = \omega_1$, from Eq. 18:

$$S_{\max} \approx \frac{V_b s(L/2)^3 \cos(\phi)/(cI_{yy}h)}{\zeta_1 \omega_1} \qquad (23)$$

The compensation filter for each microphone with sensitivity S is:

$$Compfilter = S_{max} / S \qquad (24)$$

The octave band sound pressure level with the compensation filter applied is (Fig. 5):

$$SPL_{obcomp} = 10\log_{10} \frac{p_s^2 \Delta f \cdot Compfilter^2}{p_{ref}^2} \text{ dB} \qquad (25)$$

The compensated dBA noise of the differential microphone is

$$N_{comp} = 10\log_{10} \frac{\sum_{i=5}^{10} 10^{(SPL_{obcomp_i} + Aweight_i)/10} \cdot p_{ref}^2}{p_{ref}^2} + 10\log_{10} P_{sd}$$

$$= 10\log_{10} (\sum_{i=5}^{10} 10^{(SPL_{obcomp_i} + Aweight_i)/10}) + 10\log_{10} P_{sd} \qquad (26)$$

5.0 RESULTS AND DISCUSSION

In this section predicted results for the sensitivity and noise performance of the Ormia microphone are compared with the conventional design as shown in the following figures. The calculations are based on a linear analysis.

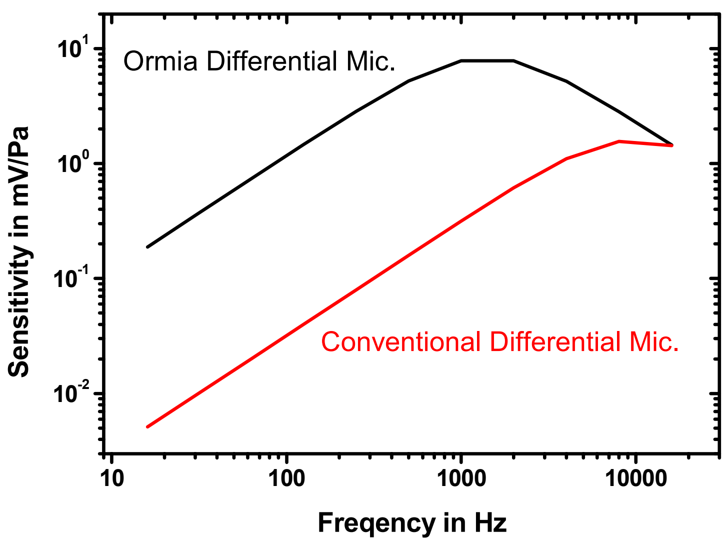


Figure 4 Predicted frequency responses of the differential microphones

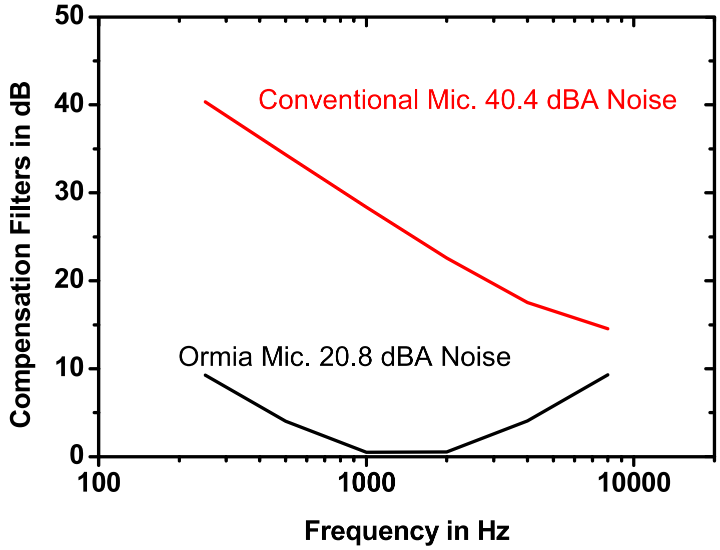


Figure5 Compensation filter responses to achieve flat frequency response

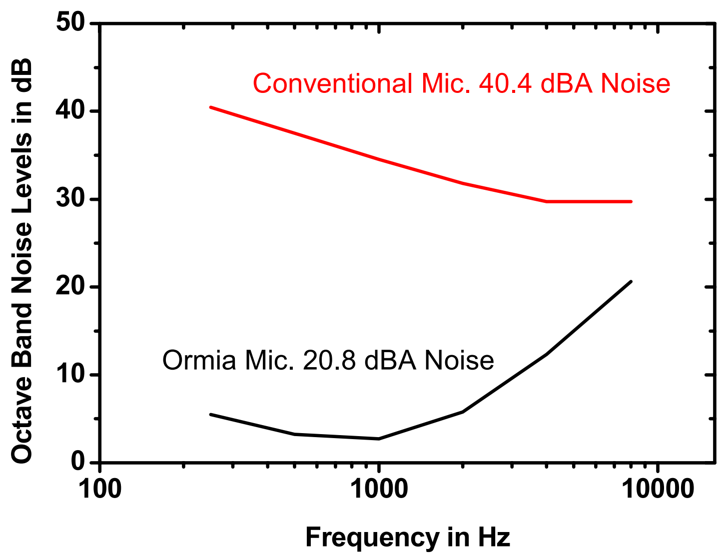


Figure 6 Predicted output noise spectra of the differential microphones

The dimensions of the microphones are both $1mm \times 2mm$, and the structures are constructed out of $1\mu m$ thick polysilicon. Both microphones thus have the same area. For the Ormia microphone, the total mass is $m = 0.975\times10^{-8}$ *kg*, the mass moment of inertia about the axis through the supports (Y axis) is $I_{yy} = 3.299\times10^{-15}$ kgm^2, The resonant frequency of the rotational mode is predicted to be 1409.3*Hz*. For the conventional microphone, the mass is $m_0 = 0.46 \times 10^{-8}$ *kg*, the resonant frequency of the diaphragm is found to be about *10kHz*. The bias voltage $V_b = 1$ *volts* and the backplate gap $h = 3\mu m$. The damping constant in each design are selected to achieve critical damping, i.e. $\zeta = 1$.

The peak of the sensitivities always appears near the resonant frequency of the system, thus the compensation filters and noise levels are lowest near this point. The sensitivities of the Ormia microphone are over one order of magnitude higher than conventional microphone at majority of the frequency range. The low signal level of the conventional microphone at low frequencies causes it to require about 40 dB of gain. It can be seen that because the use of the particular mechanical structure in the Ormia microphone, the frequency response and the noise performance are considerably improved over the conventional approach.

References

1) Miles, R. N., Robert, R., and Hoy, R. R. [1995] "Mechanically coupled ears for directional hearing in the parasitoid fly *Ormia ochracea.*" *Journal of the Acoustical Society of America* 98 (6) 3059-3070.
2) A. Mason, M. Oshinsky, and R. Hoy, "Hyperacute directional hearing in a micro-scale auditory system," *Nature* 4/5/01
3) Gabrielson, T. [1993] "Mechanical-thermal noise in micromachined acoustic and vibration sensors." *IEEE Transactions on Electron Devices* 40 (5) 903-909.